PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Improvements relating to Stress-responsive Birefringent Elements

We, INTERNATIONAL BUSINESS MACHINES CORPORATION, a Corporation organized and existing under the laws of the State of New York in the United States of America, of Armonk, New York 10504, United States of America, do hereby declare this invention, for which we pray that a patent may be granted to us and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a phase retardation device and particularly to such device including apparatus for applying a uniform stress to a stress-responsive birefringent member to cause the birefringent member to act as a quarter-wave or half-wave plate over a wide range of frequencies.

Quarter-wave or half-wave plates are utilised to change the polarization of electromagnetic radiation in wavelength regions which include the visible spectrum, infrared and ultraviolet regions, and the microwave spectrum. These plates are most familiar in the optical physics laboratory where experiments relating to the different kinds of polarization of light are performed utilising both quarter-wave and half-wave plates. Other familiar applications take advantage of the ability to control the polarization of light in filter arrangements, sunglasses and the like. One of the difficulties encountered in utilising quarter-wave plates to change the polarization of light is that the quarter wave plate is usually cut to an odd multiple (say 97) of quarter wavelengths at a given frequency. Under such circumstances, the desired polarization changes can be obtained only at this single frequency, since the variation of refractive index with frequency is so large than 90° phase-retardation is obtained only over a band of few per cent wide and over a very small angular aperture. Since these quarter-wave plates are rather costly, a number of them for use in different frequency ranges can be quite expensive. Efforts to extend to the frequency range of quarter-wave plates by the use of stress-birefringent members have not met with success. Certain applications of the phenomenon of stress birefringence utilize plasticised organic material which, in response to an applied stretching force, are capable of providing retardation of a component of light up to one-half wave-length at a given frequency. Arrangements of this type, however, suffer from the fact that they are not ordinarily useful as retardation devices to the broad spectral range from ultra-violet through infra-red. Other arrangements utilize a plurality of birefringent elements in combinations with stress responsive birefringent elements to provide optical filters having discrete outputs over a relatively narrow range of frequencies. This arrangement utilizes a number of fixed and variable birefringent elements, all of which are individually incapable of providing retardations over a wide frequency range. Stress-birefringent members, it should be recalled, vary the polarization of light impinging thereon in response to force applied by means of thumb screws to one edge of such members, electric fields or the like. Naturally birefringent materials require no application of force, but, by virtue of their crystalline structure, act to apply a relative retardation between the components of a plane polarized wave.

It is, therefore, an object of this invention to provide an improved phase retardation device.

According to the present invention there is provided a phase retardation device for use with electromagnetic radiation comprising a phase retardation plate having stress-inducible birefringent properties, pressure appa-

ratus for applying stress to the plate and stress distribution means disposed between the plate and the apparatus to distribute the stress uniformly along an edge of the plate.

Various embodiments of the invention will now be described by way of example with reference to the accompanying drawing in which:—

Fig. 1 is a front and sectional view of a simplified model of a phase retardation plate which is capable of acting as a quarter-wave or half-wave plate over a wide range of wavelengths in response to the application of a compressive stress on the plate.

Fig. 2 is a partially cut-away plan view of a variable phase retardation plate with its cover plate removed to show the internal arrangement of the elements of the device, and

Fig. 3 is a perspective view of a wedge of the pressure applying means.

A phase retardation plate having a retardation of 90° is utilized to convert linearly polarized light to circular polarized light and vice-versa and is called a quater-wave plate. A phase retardation plate having a retardation of 180° is called a half-wave plate and is utilized generally to convert linearly polarized light to light linearly polarized but perpendicular to the original direction of polarization. Linearly polarized light may be considered as the summation of component vectors which are in space quadrature but in the same time phase. Circularly polarized light may be considered as two component vectors which are in time and space quadrature. In the linearly polarized condition, the component vectors provide a linearly polarized wave which varies in a half wavelength for zero to a maximum value and back to zero. For the remaining half wave-length, the polarized wave varies from zero to a maximum of opposite polarity to the first maximum and back to zero to complete a single cycle. In the circular polarized mode, the vectors which are in time and space quadrature appear to change their direction of polarization every 90° as they pass a stationary observer giving the appearance, in one cycle, of rotating from a vertical to a horizontal, to a vertical of opposite polarity to the first vertical, to a horizontal of polarity opposite to the first mentioned horizontal polarity and back again to a vertical of a polarity the same as the first mentioned vertical polarity.

The conversion from linear polarization to circular polarization can be attributed to the introduction of a relative phase retardation of 90° to one of the component vectors mentioned in connection with the linearly polarized wave. This relative delay can be applied to one of the components by naturally birefringent materials such as crystalline quartz and calcite. Thus, a linear polarized wave impinging on a quarter-wave plate (the principal axes of which are at 45° to the polarization of the light) has one of its component vectors delayed with respect to the other component by 90°, thereby providing circularly polarized light. A distinction is made between the two vectors by the material itself, which has different electrical properties along the two directions of the polarization of the component waves.

Referring now to Fig. 1, there is shown a simplified model of a phase retardation plate which is capable of acting as a quarter-wave or half-wave plate over a wide range of wavelength in accordance with the teaching of the present invention. A transparent plate 1 of fused quartz or other suitable material is shown in Fig. 1 cradled in notches 2 of stress-applying members 3. Notches 2 extend lengthwise of plate 1 so that a tight fit is attained between notches 2 and horizontal edges of plate 1. A hydraulic member 4 is disposed between each of the horizontal edges of plate 1 and the bottoms of notches 2. Hydraulic member 4 may be any incompressible or compressible fluid or even a solid material which is subject to cold flow under high pressure and is substantially incompressible. One arrangement which has proved useful is a hollow tube of silicone rubber filled with mercury. The walls of the tube should be made as thin as possible so that the edge of plate 1, to all intents and purposes, is essentially in contact with a fluid medium. Tube walls approximately 15 mils thick have been used to provide improved results over instances where thicker tube walls were used. The tube should conform to the shape of the bottoms of notches 2 and should fit tightly within the notches 2. The tight fit between hydraulic members 4 and notches 2 and between the edges of plate 1 and notches 2 prevents extrusion of the rubber tube and escape of the fluid between the adjacent touching surfaces of plate 1 and notches 2.

Bolts 5 pass through holes 6 which are suitably drilled in the upper stress member 3. Bolts 5 are receivable in screw-threaded holes 7 which are disposed in the lower stress member 3. Washers 8 are disposed between the heads of bolts 5 and the surface of the upper stress member 3. The washers 8 uniformly distribute the forces to the upper stress member 3. In this way, local deformations and undue stress in the region of holes 6 are minimized. Bolts 5 are utilized to apply a force to the plate 1 to the point where the phenomenon of stress birefringence will appear with the application of slightly more pressure. Bolts 5 apply, in effect, a biasing stress which is not sufficient to cause a disorientation of the molecular structure of the fused quartz plate 1. Thumb screw 9 penetrates the upper stress member 3 to the bottom of the notch 2 disposed therein and butts up against hydraulic member 4. The applied pressure is trans-

ferred to all portions of the hydraulic member 4 through either the use of a confined fluid or a material which exhibits the characteristic of cold flow when subjected to pressure. Tetrafluoroethylene fluorocarbon resin or fluorinated ethylene-propylene material sold under the Trade Mark "Teflon" is one material which exhibits such a characteristic.

The pressure transmitted to hydraulic members 4 is uniformly distributed along the upper and lower edges of plate 1 and because of the applied stress, the usual molecular arrangement of the fused quartz plate is disturbed and the property of birefringence is artificially introduced. For any given setting of the thumb screw 9, a relative retardation of one of the components ofa polarized wave of 90° or a quarter-wave can be obtained. Thus, at that wavelength and only at that wavelength, the retardation is equal to one quarter wavelength. By adjusting the thumb screw 90, the relative retardation of one component of light at a different wavelength is one-quarter wavelength. Thus the plate 1 acts as a quarter-wave plate for any given setting of thumb screw 9 over a wide range of wavelengths. The range of wavelengths in excess of several thousand angstroms is a substantial improvement over the quater-wave plate combinations referred to hereinabove which provide variation over a range of only several hundred angstroms. Thus, by virtue of the use of an hydraulic member, a variable uniform stress can be applied to fused quartz plate to permit the plate to act as a quarte-wave plate over a range of frequencies larger by an order of magnitude than prior art devices. It should be obvious that it is possible to obtain similar variations where the phase retardation plate provides a delay of one-half wave length. A quarter wave length at a given frequency is equal to approximately a half-wave length retardation at a frequency which is twice the given freqnency.

Referring now to Fig. 2 there is shown a preferred embodiment of a variable phase-retardation plate in accordance with this invention. Elements in Fig. 2 have been given the same reference characters as the corresponding elements in Fig. 1. Fig. 2 shows a partially cut-away plan view of a variable phase retardation plate with its cover plate removed to show the interior arrangement of the elements of the device.

The plate 1 is shown in Fig. 2 disposed within a well 10 which is machined to a given depth in a block 11 which may be made of aluminium or other suitable material. The depth of the well 10 corresponds to the thickness of the plate 1, the thickness of which is in turn governed by the optical criteria which must be met. The width *w* of plate 1 is slightly smaller than the width of the well 10 providing a slip-fit relationship between plate 1 and the edges 12 of the well 10. An aperture 13 shows as a dotted line in Fig. 2 acts as a window through which the light to be delayed enters the device. A corresponding aperture in the cover plate (not shown) is disposed in registry with the aperture 13 forming a window on the opposite face of plate 1 from the aperture 13. The well 10 at the left-hand side thereof contains a slot 14 of the same depth as the well 10 into which an hydraulic member 4 is receivable. Hydraulic member 4 conforms with the shape of the slot 14 and is contiguous with an edge of the plate 1. As mentioned in connection with the hydraulic member of Fig. 1, the member 4 may be any incompressible or compressible fluid or even a solid material which is subject to cold flow under high pressure and is substantially incompressible. A preferred arrangement utilizes a tube of silicone rubber containing mercury. The ends of the tube are stoppered with rubber plugs which are retained in place by portions of the slot into which the member 4 is placed. The well 10 at the righthand side thereof is adapted to receive an hydraulic member 4 similar to the member in the slot 14. One side of the member 4 is contiguous with the right-hand edge of the plate 1 while the other side is contiguous with an anvil portion 15 of a wedge 16 which latter element is utilized to apply a compressive force through the member 4 to the plate 1. In this manner, the force applied to the wedge 16 is uniformly distributed along the edges of the plate 1 by means of the hydraulic member 4 so that the molecular arrangement of the plate 1 is disturbed in a uniform manner everywhere in the plate 1 and the property of birefringence is artificially produced. The wedge 16 forms a part of a mechanical arrangement which is used to apply pressures up to 2,500 lbs/sq. in. to the plate 1 and will be explained in detail in what follows.

Fig. 3 shows a perspective view of the wedge 16, which is machined from aluminium or other suitable material and includes an anvil portion 15 which is receivable in the right-hand side of the well 10 in Fig. 2. The anvil portion 15 fits tightly between edges 12 and its surface is tightly held against an adjacent hydraulic member 4.

Because of the tight fitting relationship between the member 4 and the edges 12 of the well 10 it is possible to utilize a tube of silicone rubber of substantially square cross section which may be filled with mercury and stoppered at both ends by rubber plugs. A material subject to cold flow such as Teflon (Trade Mark) may also be utilized. The anvil portion 15 is of the same thickness as the hydraulic member 4 and the plate 1.

In Fig. 3, the wedge 16 has a bearing support portion 17 at the extremities of which bearing elements 18 contact the inclined surface 19 of a wedge 20 shown in Fig. 2. A

single bearing element contiguous with surface 19 along the length thereof can be utilized, but the bearing elements 18 disposed at the extremities of the support portion 17 reduce the friction between the bearing elements 18 and the surface 19. The mechanical arrangement for driving the wedge 20 is therefore simplified. As shown in Fig. 3, the bearing support portion 17 is of greater thickness than the anvil portion 15 and is receivable in a milled-out portion 21. A portion similar to the milled-out portion 21 is machined in a cover plate (not shown) which fits over the front of block 11, which portion registers with the corresponding portions of the milled-out portion 21.

The wedge 20 has bearing elements 22 which contact an edge of the milled-out portion 21 both in the block 11 and at similar points in the milled-out cover plate (not shown). A Teflon (Trade Mark) pad 23 is interposed between the bearing elements 22 to reduce the friction between the wedge 20 and the edge of the milled-out portion 21. A screw-threaded shaft 24 disposed in a tapped hole 25 in wedge 20 passes through block 11 via an aperture 26 and is held in axial alignment by a retaining collar 27 which in turn is held in fixed relationship with a block 11 by screws 28. A shoulder 29 extending from shaft 24 establishes the vertical alignment of the shaft 24 with respect to a knob 30. Bearings 31 which may be of bronze or other suitable material permit the shoulder 29 and the knob 30 to rotate smoothly when the shaft 24 is turned by the knob 30. The knob 30 is fixed with respect to the shaft 24 by a set screw 32.

In Fig. 2, the wedge 16 has its upper extremity butted against a lip 33 formed during the machining of milled-out portion 21. A corresponding lip in the cover plate (not shown) also engages the extremity of wedge 16 when the cover plate is mated with the block 11.

In Fig. 2, wedges 20 and 16, respectively, are shown in the position of maximum pressure. The screw-threaded shaft 24 has drawn wedge 20 against the upper wall of milled-out portion 21 and all the force generated is applied to the hydraulic member 4 by the motion of the anvil 15 against it. Since wedge 16 is restrained by the lip 33 of the milled-out portion 21 and by the action of the sides 12 of the well 10 on the anvil portion 15, the motion of the wedge 20 in one direction causes the wedge 16 to move in a direction perpendicular to the motion of the wedge 20.

The foregoing description has indicated how the phenomenon of stress birefringence when artificially introduced can provide the ability to act on the polarization characteristic of light. A device including means for uniformly applying stress to a fused quartz plate has also been explained. The device, because of the ability to apply a uniform stress can act as a quarter-wave or a half-wave plate (90° or 180° retardation of a component of the incident light) over the entire transparency range of fused quartz (1800 Å to 3500 Å). As a quarter-wave plate, incidence light of linear polarization may be converted to left or right circularly polarized light. In the half-wave arrangement, horizontally polarized light may be converted to vertically polarized light and vice-versa.

The device of Fig. 2 has a clear aperture of approximately 4 sq. in. When the device is tuned to act as a quarter-wave plate, the retardation obtained is within $\pm 2°$ over a spatial aperture within an angular aperture of $\pm 30°$ and over a wavelength range of 2%. Because of possible variation in phase delay with variations in temperature, the device of Fig. 2 will provide optimum results if utilized in a thermally stable environment.

The quarter-wave and half-wave plate has many traditional uses in optics but their usefulness was limited because, in the past, they were neither tunable nor inexpensive. The present device while it is both tuntable and relatively inexpensive offers further advantages which make such devices applicable to present day technology. In the laser field, for instance, the device of the present application can be most useful because, in addition to a very high power handling capability, there is no second harmonic content in the beam.

WHAT WE CLAIM IS:—

1. A phase retardation device for use with electromagnetic radiation comprising a phase retardation plate having stress-inducible birefringent properties, pressure apparatus for applying stress to the plate and stress distribution means disposed between the plate and the apparatus to distribute the stress uniformly along an edge of the plate.

2. A device according to claim 1 wherein the plate is fused quartz.

3. A device according to claim 1 or claim 2 wherein the stress distribution means includes a fluid.

4. A device according to claim 3 wherein said fluid is an incompressible fluid.

5. A device according to claim 4 wherein said fluid is mercury.

6. A device according to claim 3 wherein said fluid is a compressible fluid.

7. A device according to any one of claims 3 to 6 wherein said fluid is contained within a hollow flexible member.

8. A device according to claim 1 or claim 2 wherein the stress distribution means includes a solid material subject to cold flow under pressure.

9. A device according to claim 8 wherein said material is tetrafluoroethylene fluorocarbon resin or a fluorinated ethylene-propylene resin.

10. A device according to claim 1 or claim 2 wherein said stress distributing means includes a confined fluid contiguous with said edge.

11. A device according to any one of the preceding claims wherein said pressure apparatus includes a pressure applying member which contacts said stress distributing means.

12. A device according to claim 11 wherein said member contacts said stress distributing means at a single point along the length thereof.

13. A device according to claim 11 or claim 12 wherein said member includes a wedge constrained to move in a given direction to apply a force along the length of said means and a second wedge constrained to move in a direction perpendicular to said given direction, the inclined surface of which contacts the inclined surface of said first mentioned wedge.

14. A device according to any one of the preceding claims further including means for varying the stress applied to said plate to vary the wavelength at which phase retardation occurs over a wide range of wavelengths.

15. A phase retardation device substantially as herein described with reference to Fig. 1 or Fig. 2 and Fig. 3 of the accompanying drawing.

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1 SHEET *This drawing is a reproduction of the Original on a reduced scale*

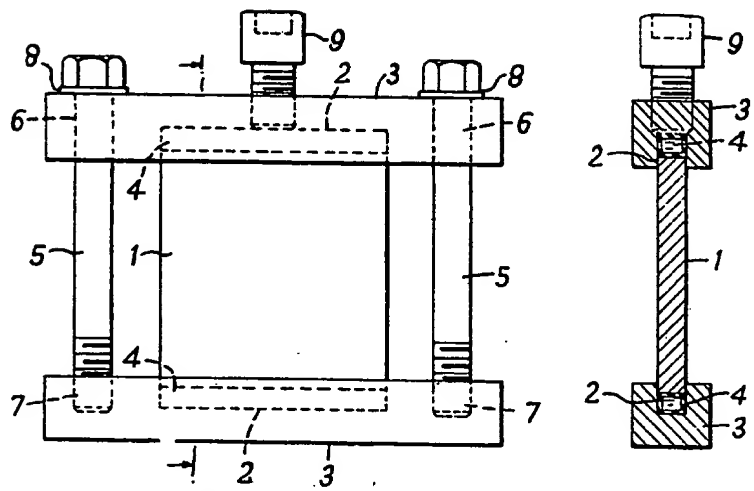

Fig.1.

Fig.2.

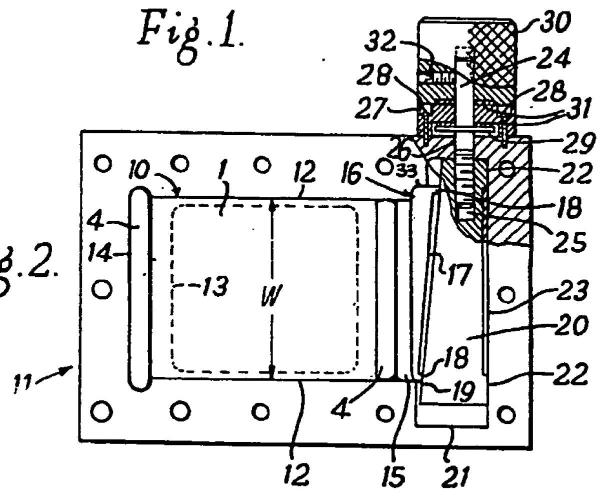

Fig.3.